Evans

The mixing of a hot pulsating air jet in a cold secondary air flow.

THE MIXING OF A HOT PULSATING AIR JET IN A COLD SECONDARY AIR FLOW

A Thesis
Submitted to the Graduate Faculty
of the
University of Minnesota

by
Richard L. Evans

In Partial Fulfillment of the Requirements for
the Degree of
Master of Science in Aeronautical Engineering

June, 1952

To my wife, Florence, without whose aid and support the past three years of studies would have been impossible.

It is desired to express appreciative acknowledgement for the assistance, advice and counseling of Dr. N. A. Hall, Prof. J. A. Wise and Prof. T. W. Murphy.

TABLE OF CONTENTS

PAGE

SUMMARY. 1

INTRODUCTION 2

EQUIPMENT AND PROCEDURE. 6

RESULTS AND DISCUSSION 10

CONCLUSIONS AND RECOMMENDATIONS. 16

TABLES AND FIGURES 17

BIBLIOGRAPHY 30

APPENDIX 32

SUMMARY

The investigation which is the subject of this thesis was undertaken to examine the mixing of a heated air jet pulsating at resonant frequency with a cold coaxial secondary jet.

It was desired to obtain results comparable with other investigators and, if possible, extend the field somewhat.

The results indicate that too great a step forward from known relations was attempted.

The experimentation incident to this thesis was carried out in the Gas Turbine Test Cell of the Mechanical Engineering Department of the University of Minnesota.

INTRODUCTION

This project was undertaken to examine experimentally the velocity mixing of a hot pulsating air jet and a steady cold coaxial secondary jet. Much research, both analytical and experimental, has been done in jet mixing, but little has been done on three dimensional coaxial jets and less on such configurations with a temperature differential. C. J. Burton in his Master's Thesis (1) experimentally determined the velocity mixing of an air jet pulsating at low frequency in a steady secondary air stream with no temperature difference between the two. It was felt that increasing the pulsations of the primary stream to approximately 20 cycles per second and at the same time elevating its temperature considerably above that of the secondary stream would approach in some measure certain of the conditions known to produce resonant effects in combustion chambers (2).

Even a casual study of the mixing problem reveals that basic knowledge in the field is limited. One fundamental requirement for the complete solution of the problem would be a thorough understanding of free turbulence and the mechanism of turbulent diffusion. Such understanding does not at present appear readily obtainable (3,4). However, certain phases of the general problem

open to experimental solution present themselves. It is certain that better knowledge of the phenomena incident to the mixing of coaxial jet streams would not only find application in the realm of combustion chamber design but also in that of thrust augmentors, jet pumps and mixing tanks.

As mentioned, considerable work has been done on jet mixing but relatively little of this has been concerned with coaxial jets with secondary flow. Shapiro and Forstall (5) give an extensive bibliography on the entire subject. They found that the analytical method of Squire and Trouncer (6) is at present the only practical approach to this phase of the problem. These investigators checked Squire and Trouncer's results experimentally and found that, in the main, they give a correct over all picture of the mixing process.

Ribner (7) gives an approximate solution for a variable density round jet in a moving medium by empirical generalization of the method of Squire and Trounder. He states that the local density in the hot jet will be some variable fraction of the free stream density. He assumes that the ratio of the temperature at any point in the hot jet to the free stream temperature is proportional to the ratio between the hot jet velocity at that point and the free stream velocity. It is pointed out, however, that the momentum transfer theory indicates such a distribution only follows when temperature differences are so small

that density changes and heat transfer by radiation can be neglected. Admittedly, the temperature differences were not small in Ribner's investigation.

Cleeves and Boelter (8) conducted experimental investigations of a non-isothermal air jet with an initial temperature of 1200°F. and without a secondary air stream. Their results correlated satisfactorily with the analytic determinations of others for radial velocity and temperature distributions. These authors give a resumé (to 1947) of work in the field of non-isothermal jets. Prandtl, Tollmein and Kuethe (9,10,11) developed analytic approaches using the momentum transfer theory. Taylor, Howarth and Timotika (12,13,14) approached the problem by the modified vorticity transport theory. Lin (15) solved it by assuming constant shear. Analysis based on the momentum transfer theory results in velocity and temperature distributions that are similar since the differential equations arrived at in each case are similar. Those using the vorticity transport theory, however, give the qualitatively correct result that heat diffuses more rapidly than momentum. Corrsin and Uberoi (3) confirm this statement.

If the results of Cleeves and Boelter for non-isothermal free jets and those of Shapiro and Forstall for coaxial isothermal jets can be combined and applied to the present case, it may be conjectured that the potential core length for a non-isothermal jet with coaxial secondary flow is somewhat greater than that found by the former.

The preceding brief sumary of what is known about jet mixing clearly indicates that the velocity mixing of turbulent non-isothermal coaxial jets has not yet been investigated, either analytically or experimentally. It was proposed to make such an experimental investigation the subject of this thesis.

EQUIPMENT AND PROCEDURE

The basic measuring instrument used in these tests was a stainless steel total head tube of the kiel type with a total head opening .0625 inches in diameter and venturi entrance of .37 inches in diameter. Mounted as nearly aft of the venturi discharge as could be managed without touching the metal of the tube was a bare bead iron-constantan thermocouple. This bead was estimated to have had a mean position of about one-half inch aft of the entrance to the total head tube. Temperature measurements as recorded, therefore, were actually for X/D stations one-half inch greater than those for which dynamic pressure heads were read.

The kiel tube was mounted in a packing gland screwed into a metal plate which in turn was secured by four thumb screws to a laterally movable plate in the side of the test duct. This allowed lateral and transverse motion of the kiel tube so that all sections of the flow could be reached. Centering the tube at a Y/D position of zero for each successive traverse was obtained by making electrical contact between the head of the tube and nichrome wire centered ten diameters upstream in the primary air tube and then secured to a cross piece at the far end of the test duct.

Pressures recorded by the kiel tube and static pressure tap of one-eighth inch diameter drilled into the lower portion of the movable test plate were differentially combined and translated into an electrical impulse by a Statham Low Range Pressure Transducer. The kiel tube and the static pressure tap were connected to the Statham Gage by rubber tubing of as short a length as could conveniently be arranged.

The electrical impulse of the Statham Gage was led by a shielded cable to the Brush Model 310 Strain Analyzer. Here it was amplified in accordance with the scale factor set by the operator and sent to one of the pens of a two pen Brush Magnetic Oscillograph. It was recorded as trace on the moving paper roll.

The primary air used in this investigation was obtained from the building compressed air supply. This air was connected directly to a surge tank, thence to a metering orfice and another surge tank, next to a combustion chamber and finally, to a butterfly pulsator valve and discharge. All primary air lines were two inch pipe until after the butterfly valve where the line was smoothly reduced to a one inch brass discharge pipe.

The combustion chamber was of simple construction. It was a rectangular stainless steel box approximately fourteen by four inches. About one-third the length down stream from the entrance was fitted a transverse three quarter inch iron pipe with five drill holes located in the

downstream face. Acetylene at about four to five pounds per square inch pressure was introduced into this pipe and the mixture initially ignited by a spark plug located on the top of the chamber about three inches downstream from the acetylene discharge. Discharge temperatures for the primary air were held essentially constant by adjusting the acetylene flow as dictated by the temperatures recorded by an iron-constantan thermocouple located ten diameters upstream from the primary air discharge.

Secondary air was furnished by a blower driven by a Lycoming Tank Engine. It was led from the secondary air mainfold to a surge tank through a six inch pipe fitted with a metering orfice. It was discharged from the surge tank to the test duct by a rectangular converging nozzle. Before entering the test duct, it passed through an eighteen mesh copper screen.

The butterfly valve in the primary air lines was driven by a half horse power electric motor through a variable speed drive. The shaft of the butterfly was fitted with an eccentric which lifted breaker points just as the valve was closing. These points were connected in series with a six volt battery and a Brush Amplifier. The output of this amplifier fed the second pen of the Brush Oscillograph and caused a vee-shaped notch to appear on the paper roll each time the valve closed.

Temperatures for the measuring orfices in the air supply lines, the control temperature of the combustion

chamber discharge and the temperature of the flow at the kiel tube position were all measured by iron-constantan thermocouples. A selector switch arrangement made possible the reading of these temperatures on a direct reading Brown Potentiometer Pyrometer or a more accurate Leeds and Northrup Potentiometer indicator.

A schematic sketch of the essential elements of the test equipment is given in Fig. 1. Photographs of the lay out are given in Figs. 2, 3, 4 and 5.

Making the runs required three men. One man was stationed outside the test cell at the test panel, controlling the speed of the tank engine and thus the mass flow of secondary air. The second man checked the metering orfice manometers to insure constant air supply at the desired mass flow and also made and recorded all temperature readings. The third man located the kiel tube at the desired positions and operated the Brush Recording apparatus. On his "mark" of being in position, temperature and dynamic pressure readings were made virtually simultaneously.

Two runs were made, one with and one without the butterfly valve in operation. During the run when the valve was operating the speed of the valve shaft was set at 1968 RPM which had previously been determined as the resonant frequency of the system (16). This speed was set and maintained by means of a strobotactometer and appropriate marks on the valve drive shaft pully.

RESULTS AND DISCUSSION

The data resulting from the two runs made are presented in Tables I through IV. Tables I and II list the dynamic pressure, temperature and velocity of each point measured in the steady flow case. Tables III and IV give the same information on the pulsating flow case with the addition of the dynamic pressure and velocity of the amplitude of pulsation.

On first reducing the data a discrepancy in velocities was noted. The mass flow for the primary and secondary air had been set so as to give 160 and 80 feet per second respectively at the expected discharge temperatures. The observed velocities exceeded these values by as much as 40 feet per second. The cause of this wide variance is the extreme non-linearity of the temperature profiles. Referring to Table I, at an X/D position of zero,it is seen that across the half inch radius of the primary air discharge pipe the temperature varied almost 400°F. This was most unfortunate, and made any direct comparison with work of other investigators difficult. S. Corrsin and M. S. Uberoi (4) particularize the manner in which they obtained a linear temperature profile for their investigation of a heated air jet. W. Forstall and A. H. Shapiro (6), while working with isothermal jets, took precautions to insure

linear velocity profiles for their entrance air. E. A. Robie (16 - Master's Thesis, University of Minnesota, 1952) using the same apparatus as described here, but working with isothermal jets, obtained reasonable linearity for his velocity profiles.

As a first attempt to reduce the data to usable form, dynamic profiles for each station traversed were drawn. Fig. 6 is a sketch of six of these profiles, three from each run, at X/D's of 0, 5.0 and 12.0. Dynamic pressure was selected as a promising starting point as it is a combination of density and velocity variables of the flow.

Examination of these q profiles shows rather marked differences between the steady and the pulsating flow. At an X/D of zero, the pulsed flow has a definite tendency to concentrate the flow energy along the Y/D equal zero axis. At succeeding downstream stations, the pulsed flow does not appear to reach a near linear distribution of dynamic pressure as rapidly as does the steady flow. It was conceived that a linear q distribution would represent the final, complete mixing of the two streams. That is to say, the station at and after which the density, velocity and temperature respectively have equal values across the flow, would also have a linear distribution of dynamic pressure.

Since the flow investigated possessed variable density and velocity, one means of averaging these variables at a given station to get a result meaningful in fluid flow

would be to write an expression for the momentum of a fixed core of the fluid at a given station in terms of these variables.

The expression written was:

$$MV = \sum qA$$

Where q represented the dynamic pressure at successive radial distances from the centerline and A represented the annular area at each successive position. The manner of arriving at this result is shown in the Appendix.

The basic data obtained in this investigation was the dynamic pressure at various points in the flow.

It would appear that if mixing occurred, successive stations of a constant core of the fluid would lose momentum. Furthermore, this loss should be an indication of the degree and rate of mixing.

Momenta for a one inch core of the flow, which represented the primary discharge at X/D equal to zero, and for a 2.8 inch core, which included the outward limit of dynamic pressure determination at most stations, were computed for both the steady and the pulsed flow. The results are plotted in Figs. 7 and 8 as the dimensionless ratio of the momentum of the station to the momentum at discharge against axial distance.

It will be noted that the slopes for the small core are steeper than for the larger core. It is evident that if a similar process had been carried out for the entire width of the flow that no change in momentum would result

at successive axial positions and that the slope of such a plot would be a vertical line with a ratio value of one. The observed increase of slope with core diameter is thus explained.

Since there is no basis for expecting a momentum increase at increasing X/D positions for the steady flow case, ratio values in the region between X/D equal one and 5.0 can be expected to be close to one. It will be noted that in both plots of the steady flow the ratio appears to break away at station 5.0. This behavior could be explained in the incompressible flow case as a result of the ending of the potential core. A momentum ratio plot applied to such conditions would probably show that a change in the rate of momentum decrease would result after the influence of the undisturbed primary velocity had vanished. Such an investigation is suggested as a subject of possible interest for further study.

Both Fig. 7 and Fig. 8 show the rather unexpected result that the momentum for the pulsating flow in the cores chosen for study increased for some distance beyond the discharge area before it begins a regular rate of decrease. This effect is much stronger in the smaller core, which corresponds to the primary air discharge. The pulsations were initiated in the primary air. This suggests a possible inflow of secondary air into the primary core region at stations near the discharge nozzle where the pulse effects were strong.

It is difficult to draw conclusions from the relative slopes of these curves. For the one inch core, the pulsed flow indicates a more rapid rate of decrease in momentum after the point has been reached where the momentum has stopped increasing. For the 2.8 inch core the slopes appear nearly parallel. It is realized that a great many more points would be required to demonstrate beyond question which of the two flows exhibits more rapid mixing using the present method.

Figs. 9 and 10 represent dimensionless centerline velocity and temperature plots of the two flows investigated. These curves are far removed from those of such investigators as Shapiro and Forstall. Again, the excessive departure from non-linearity of the initial velocity profiles is believed to be the cause. The extreme scatter of points for the pulsating case is suspected to have resulted from considerable transverse flow from the secondary air when the butterfly valve was closed. These figures do suggest shorter "potential" cores for temperature than for velocity in both flows, a fact established by other research.

It was also desired to investigate the behavior of the pulse as it traveled the length of the duct. Fig. 11 represents the centerline amplitude decay and the dimensionless centerline temperature drop for the pulsed flow. The amplitude decay apparently shows a considerable change in rate after station 12.0. Pulse amplitudes beyond this point were variable and difficult to read, however, and

such a change may be only illustory. It is interesting to note that this decay of pulse amplitude is very much higher, on the order of four times, than that found by E. A. Robie (16) in a similar investigation of isothermal jets.

It was considered worthwhile to check the dimensionless velocity profiles of the fully developed mixing region. The resulting points were very badly scattered, and did not tend to follow either the cosine curve, the probability curve or the three halves power curve. They are not reproduced here.

It was evident from the recordings taken that a shift in phase of the pulses occurred on a longitudinal traverse of the test duct. The manner in which the data was recorded, however, made a quantitative measure of this phase shift impractical.

CONCLUSIONS AND RECOMMENDATIONS

1. It is concluded in accord with other investigators that the thermal potential core is shorter than the velocity potential core for both steady and pulsating coaxial non-isothermal air jets.

2. The methods of reducing the data of the present investigation furnish a basis for comparing the two types of flow studied.

3. The present investigation indicates that pulsating primary air jet probably mixes more rapidly with the steady secondary air than does a steady primary jet.

4. A phase shift occurs in pulsation along the centerline as the flow progresses.

5. An investigation similar to the present, but with beginning linear temperature and velocity profiles, would yield results more readily comparable with previous work.

6. An investigation with non-linear beginning profiles but based on data from considerably more transverse stations would be of interest.

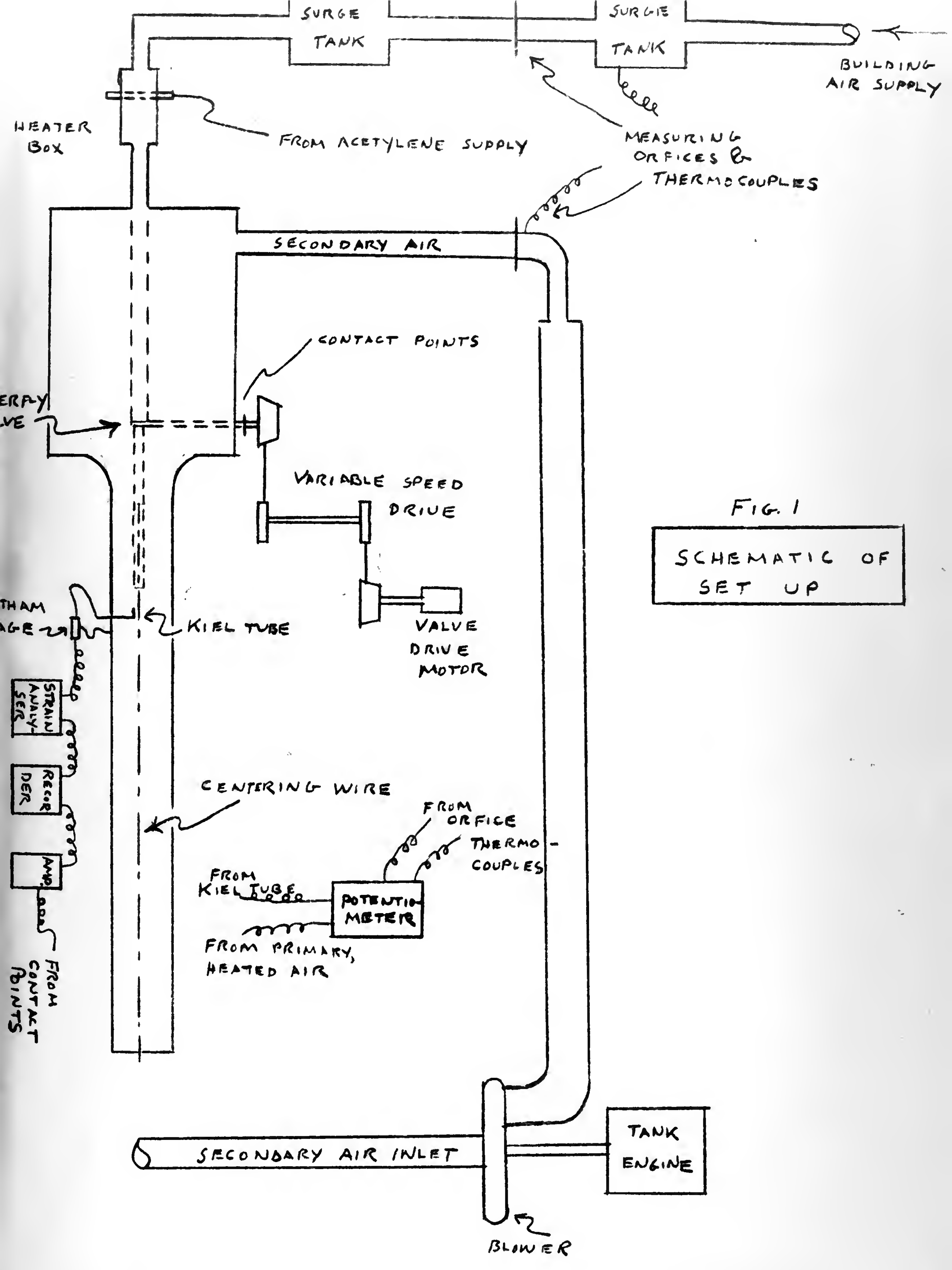
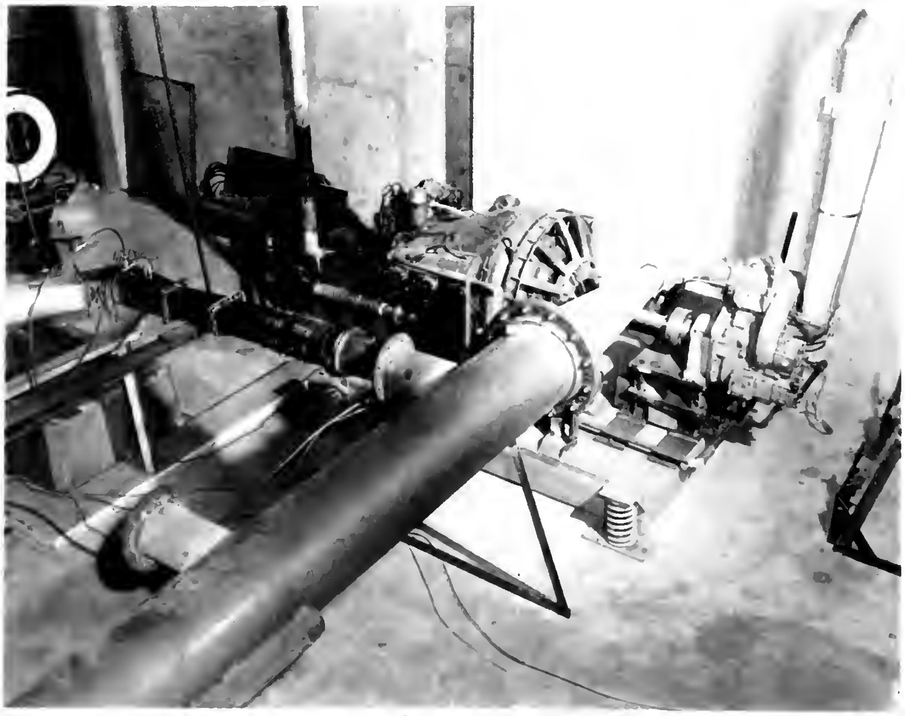
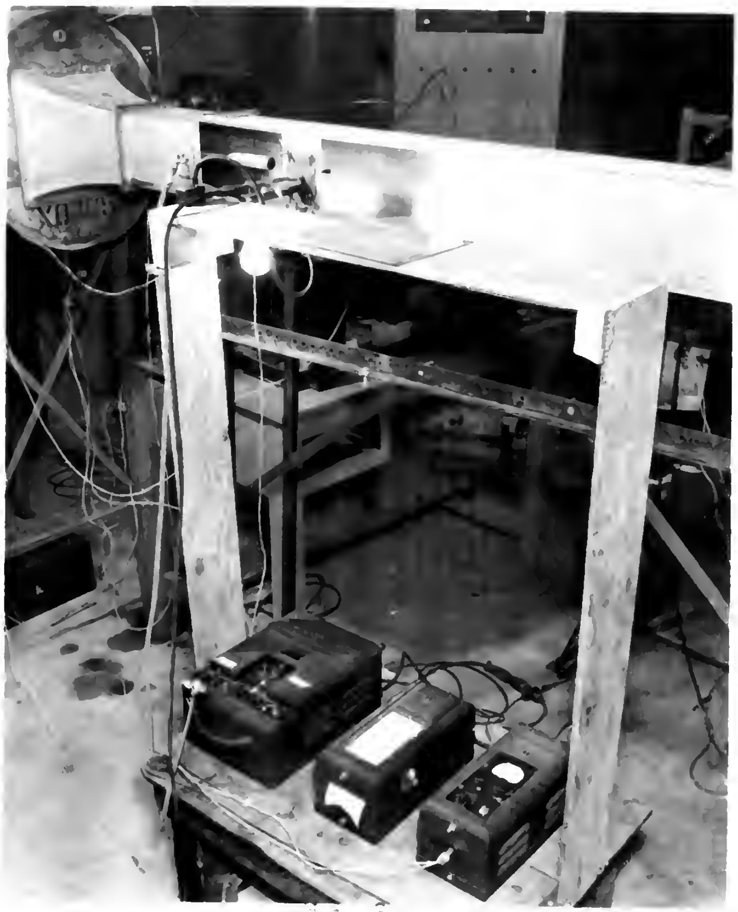


FIG. 1

SCHEMATIC OF SET UP





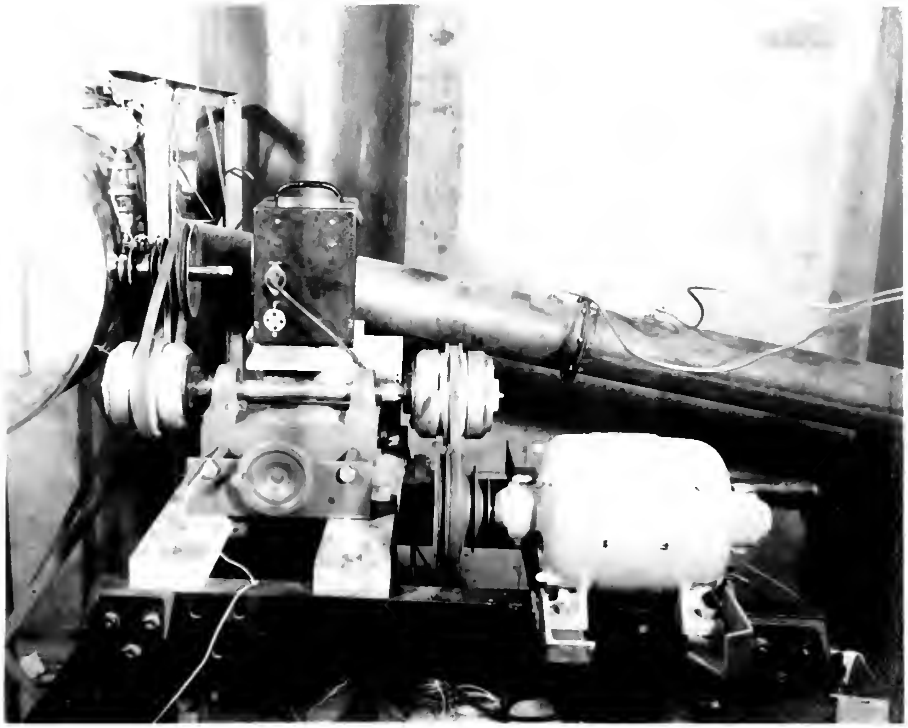


Fig. 1

[illegible]

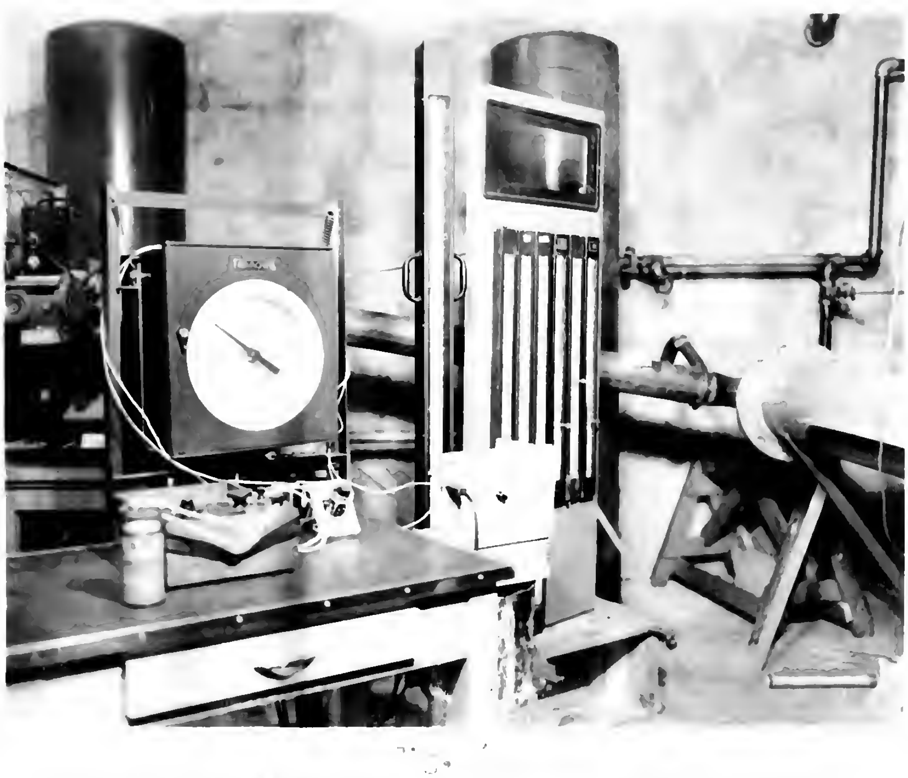
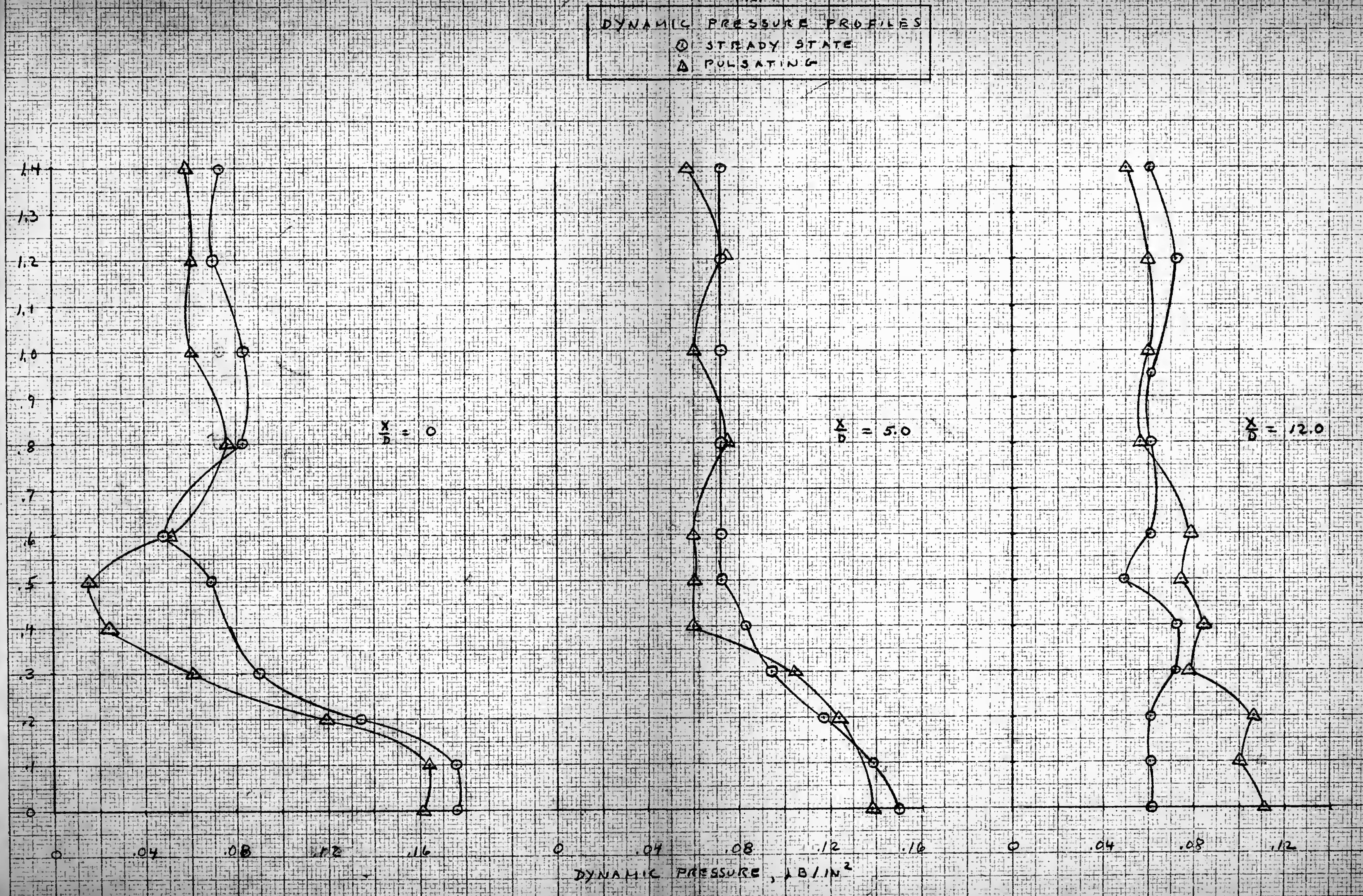


Fig. [illegible]

[illegible]

FIG. 6



DYNAMIC PRESSURE PROFILES
STEADY STATE
PULSATING
X/D = 0
X/D = 5.0
X/D = 12.0
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
0
.04
.08
.12
.16
DYNAMIC PRESSURE, LB/IN^2

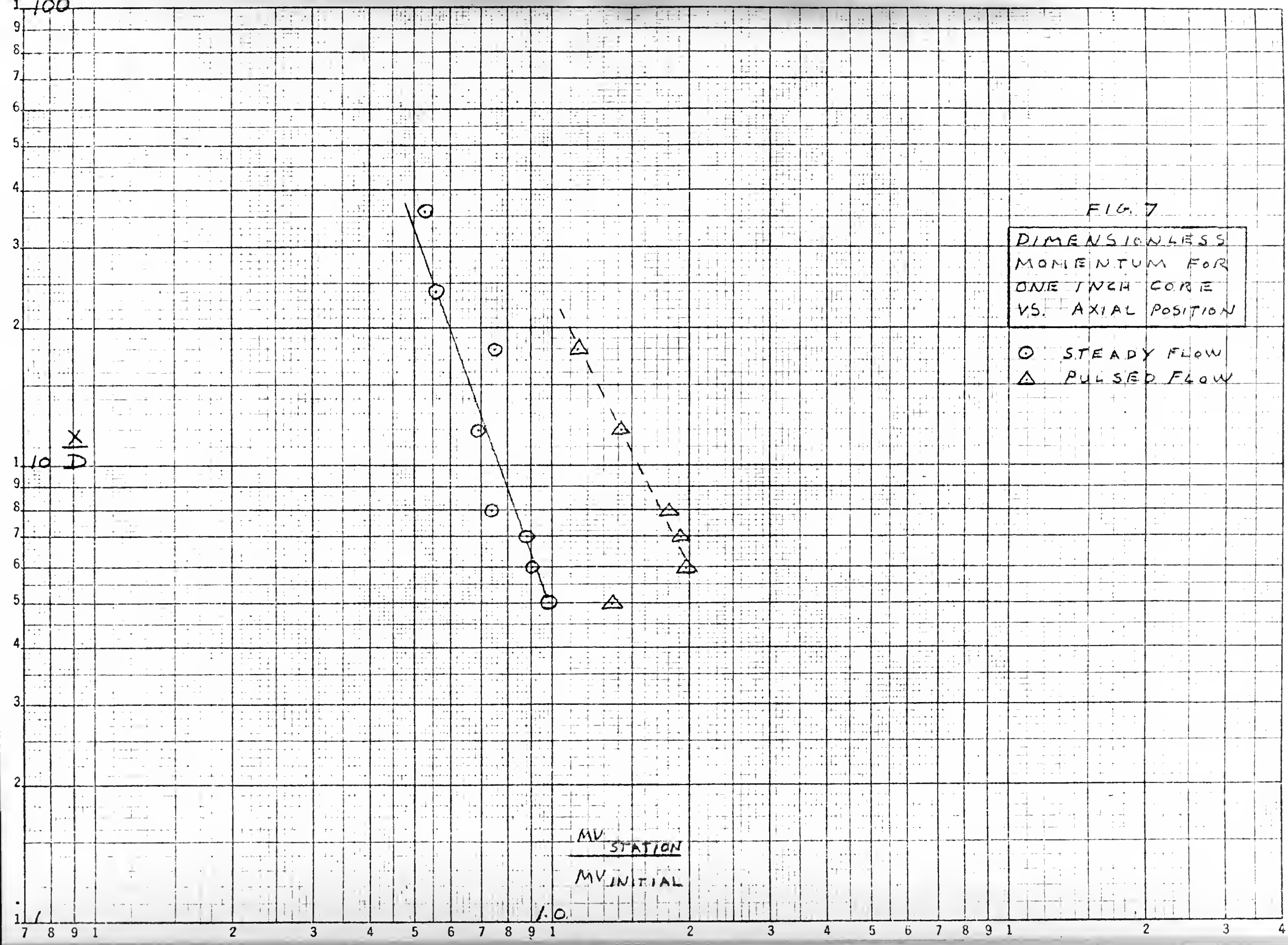


FIG. 7
DIMENSIONLESS MOMENTUM FOR ONE INCH CORE VS. AXIAL POSITION
⊙ STEADY FLOW
△ PULSED FLOW
X/D
100
10
1
1.0
MV STATION / MV INITIAL

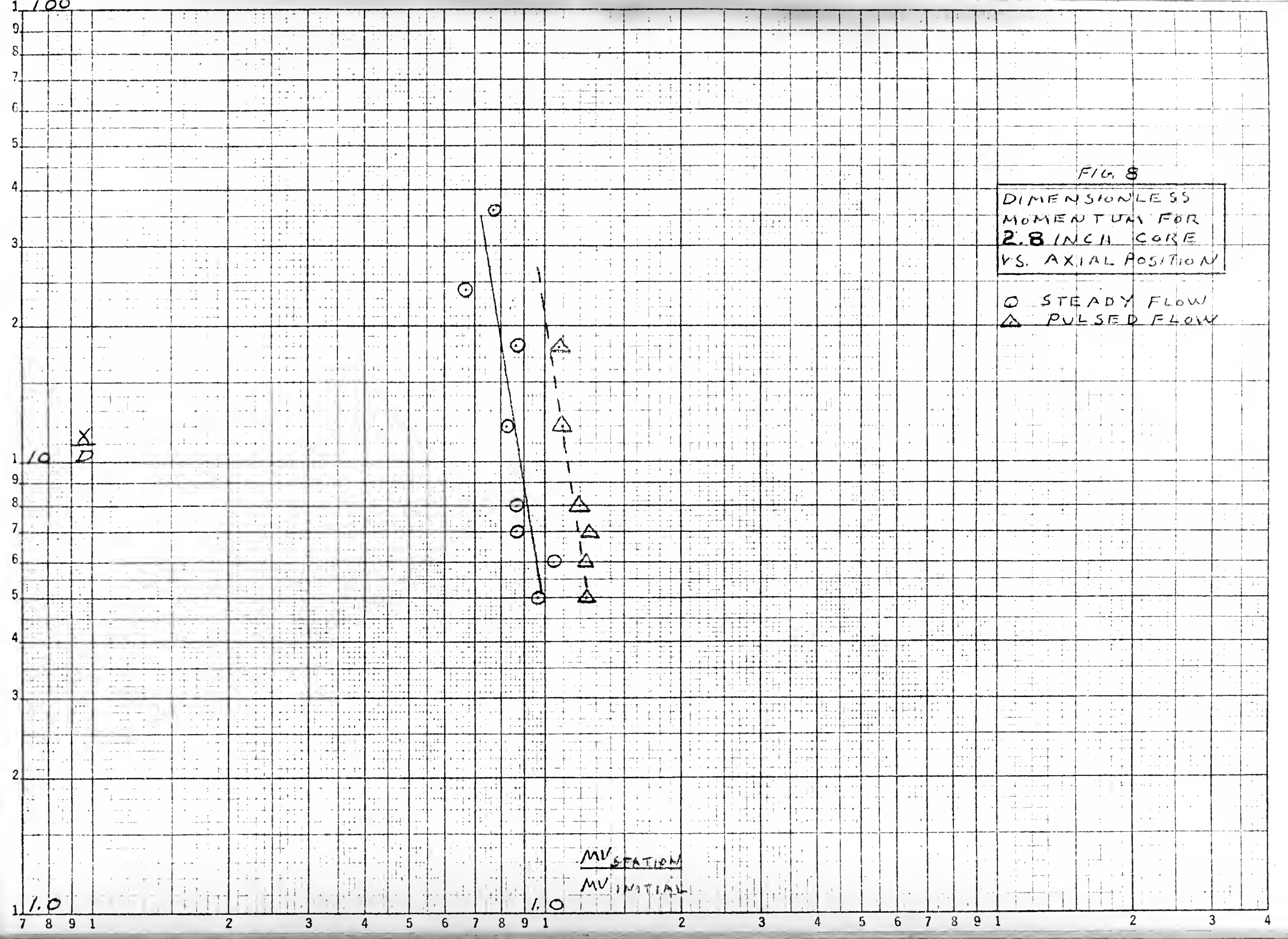
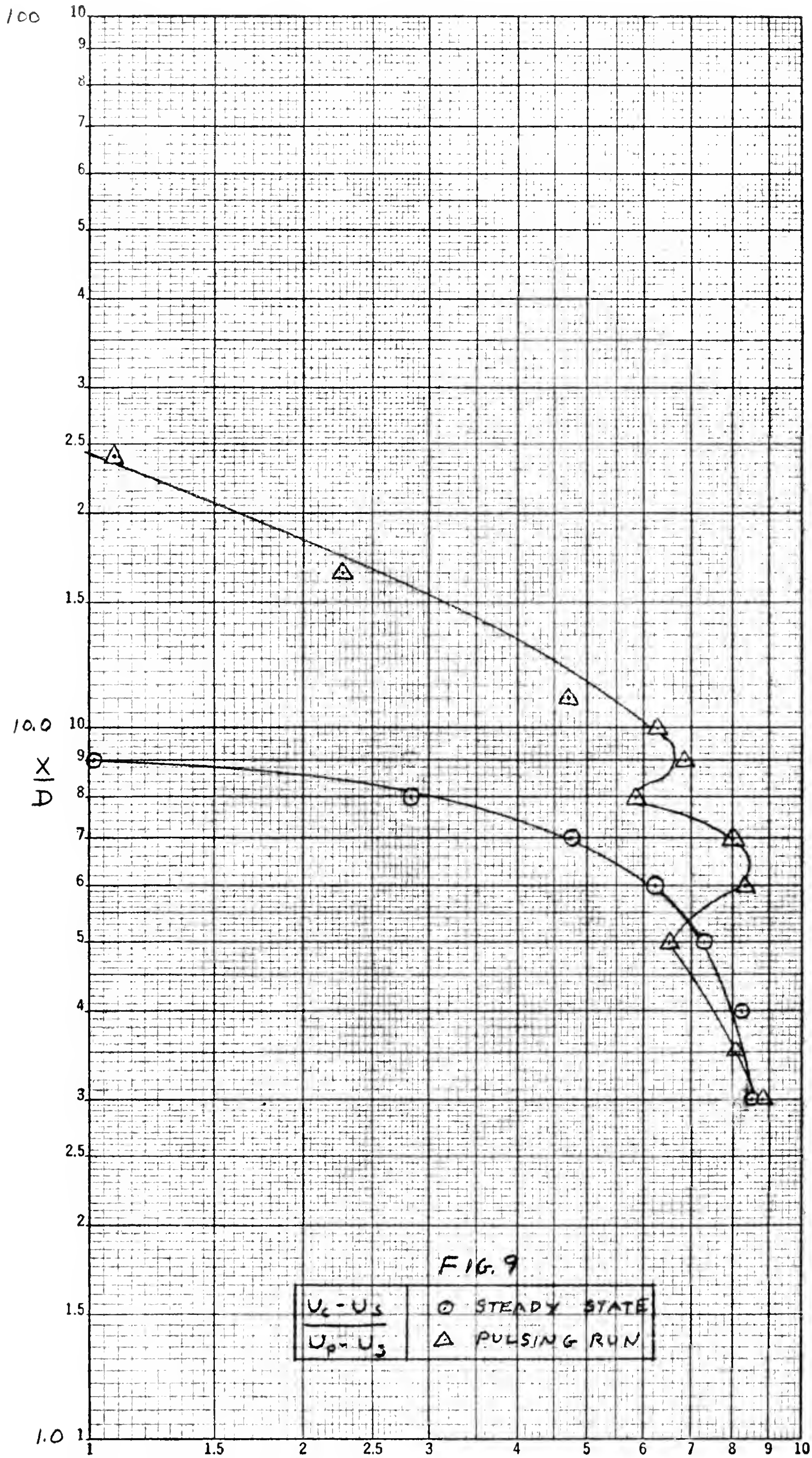
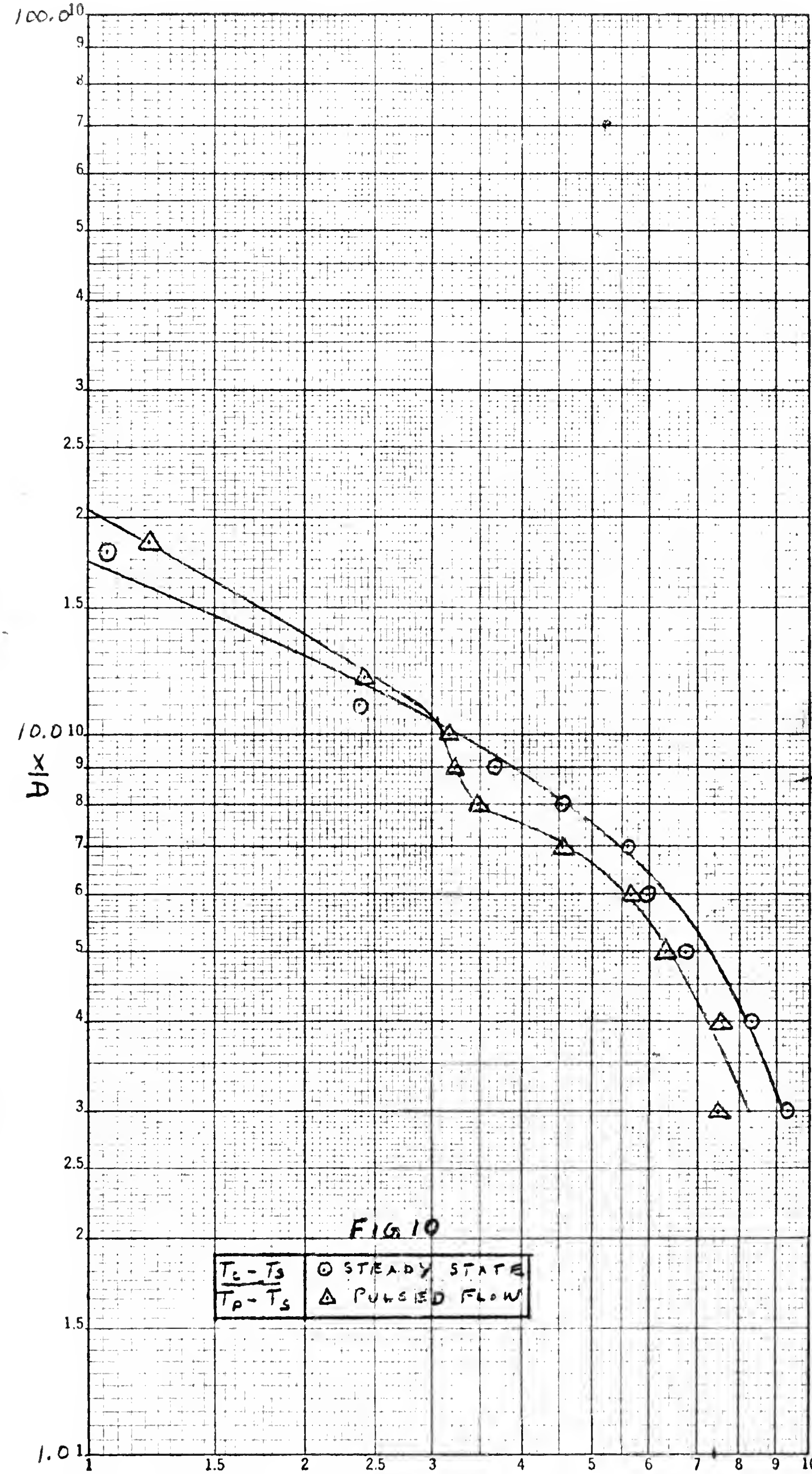


FIG. 8
DIMENSIONLESS MOMENTUM FOR 2.8 INCH CORE VS. AXIAL POSITION
○ STEADY FLOW
△ PULSED FLOW
$\frac{X}{D}$
100
10
1.0
1.0
$\frac{MV_{STATION}}{MV_{INITIAL}}$


100
10.0
X/D
1.0
1
1.5
2
2.5
3
4
5
6
7
8
9
10
FIG. 9
$\frac{U_c - U_s}{U_p - U_s}$
⊙ STEADY STATE
△ PULSING RUN



100.0
10.0
1.0
x/D
FIG 10
$\frac{T_c - T_s}{T_p - T_s}$
⊙ STEADY STATE
△ PULSED FLOW

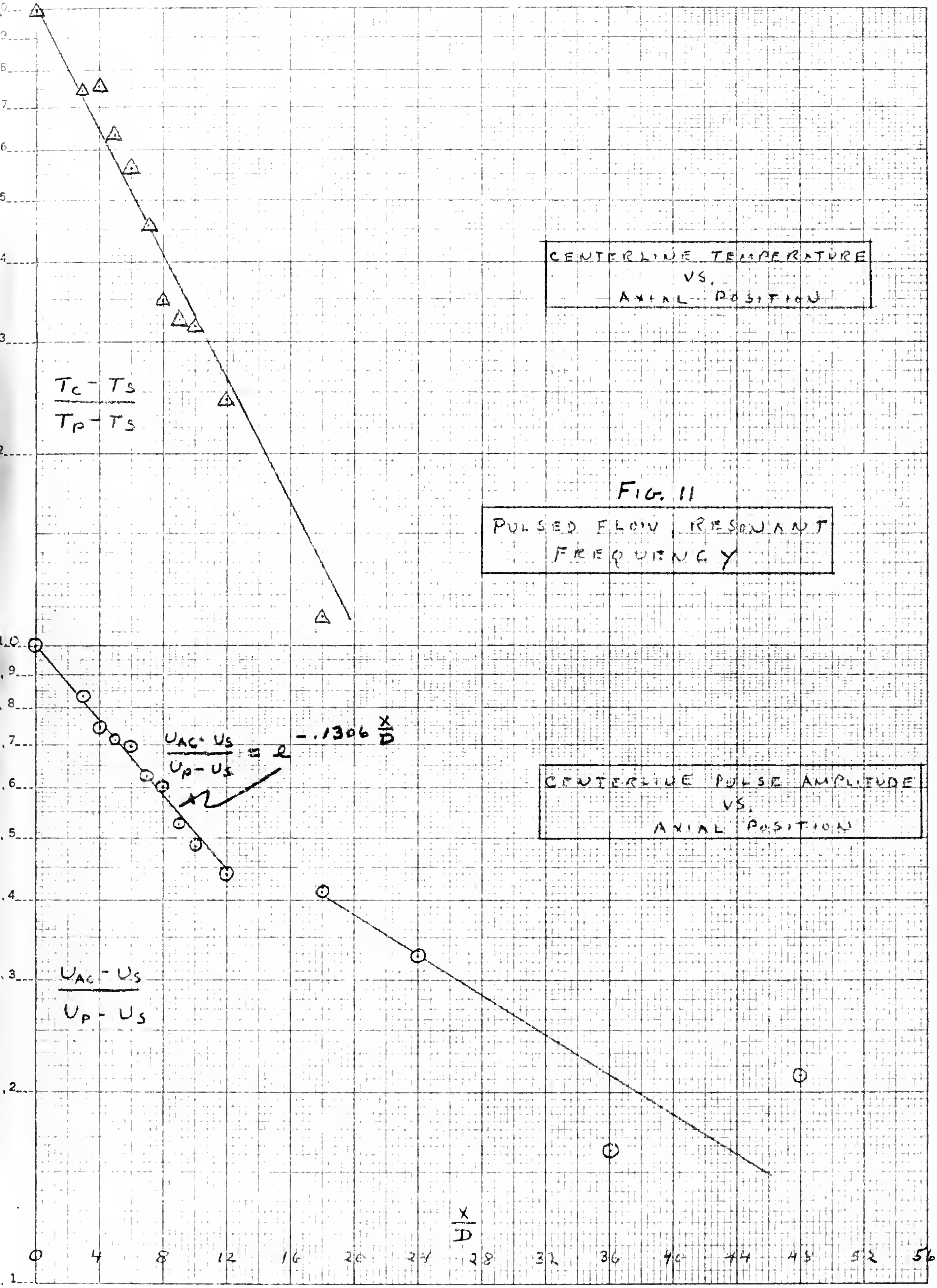

CENTERLINE TEMPERATURE
VS.
AXIAL POSITION
$\frac{T_c - T_s}{T_p - T_s}$
FIG. 11
PULSED FLOW, RESONANT
FREQUENCY
$\frac{U_{AC} - U_s}{U_p - U_s} = e^{-.1306 \frac{X}{D}}$
CENTERLINE PULSE AMPLITUDE
VS.
AXIAL POSITION
$\frac{U_{AC} - U_s}{U_p - U_s}$
$\frac{X}{D}$
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1

TABLE I

STEADY STATE FLOW																					
$\frac{Y}{D}$	$\frac{X}{D} = 0$			$\frac{X}{D} = 3.0$			$\frac{X}{D} = 4.0$			$\frac{X}{D} = 5.0$			$\frac{X}{D} = 6.0$			$\frac{X}{D} = 7.0$			$\frac{X}{D} = 8.0$		
	q LB/IN²	T °F	V FT/SEC	q	T	V	q	T	V	q	T	V	q	T	V	q	T	V	q	T	V
0	.176	535	202	.15	500	187.3	.157	465	184	.15	398	174.8	.139	365	163.8	.117	350	148.8	.094	305	129.5
.1	.176	445	189							.139	345	161.9	.128	311	151.8	.083	340	124.8	"	300	129.2
.2	.134	331	157							.117	278	142	.1055	260	133	.094	305	129.4	.083	280	119.7
.3	.09	265	123							.094	275	126.8	.094	230	130	"	270	126.4	"	250	117
.4										.083	220	119.4	.083	185	111.8	.083	225	115	.061	210	97.5
.5	.069	140	98.1							.072	160	102	"	160	109.5	.072	190	104.3	"	190	96
.6	.048	120	80.5							"	135	100	"	135	107.3	.061	165	94.5	.072	175	103.2
.8	.083	115	105.3							"	120	98.6	"	125	106.3	.0475	140	83.4	.061	140	93.5
1.0	.083	"	"							"	115	98.1	.072	115	98.1	.072	125	99.1	.0475	130	83.5
1.2	.07	"	94							"	"	"	.083	"	105.5	.061	120	90.9	.072	125	99
1.4	.073	"	98.2							"	"	"	.072	"	98.1	.072	"	98.7	.072	120	98.6
1.6																			.0885	"	109.3
1.8																			.072	"	98.6

TABLE II

STEADY STATE FLOW																					
	$\frac{X}{D}=9$			$\frac{X}{D}=10.0$			$\frac{X}{D}=12.0$			$\frac{X}{D}=18.0$			$\frac{X}{D}=24.0$			$\frac{X}{D}=36.0$			$\frac{X}{D}=48.0$		
$\frac{Y}{D}$	γ LB/IN^2	T °F	V FT/SEC	γ	T	V	γ	T	V	γ	T	V	γ	T	V	γ	T	V	γ	T	V
0	.072	270	110.9	.072	250	109.0	.061	215	98	.061	160	94	.0495	140	83.2	.061	130	91.5	.061	129	90.9
.1							"	"	"	"	"	"	"	"	"	"	"	"			
.2							"	208	97.5	.0495	"	86.6	"	"	"	"	"	"			
.3							.072	195	105	.061	158	93.7	"	"	"	"	"	"			
.4							"	185	104	"	155	93.5	.061	"	92	"	"	"			
.5							.0495	175	85.9	.072	152	101.5	.0495	"	83.2	"	"	"			
.6							.061	168	94.5	.061	"	93.4	"	"	83.2	.0495	"	82.5			
.8							"	150	93	"	145	92.8	.061	138	92.4	.061	"	91.5			
1.0							"	140	92.5	.072	140	108	.0495	135	82.8	"	"	"			
1.2							.072	135	100	"	135	100	"	"	"	"	"	"			
1.4							.061	125	91.5	"	130	99.6	"	"	"						
1.6							"	120	91	.0495	128	82.5									
1.8							.072	"	98.6	"	125	82.1									
2.0							"	"	"	"	120	81.9									

TABLE III PULSED FLOW

Y/D	X/D = 0 q (LB/IN²)	T (°F)	V_{AMP} (FT/SEC)	V_{BASE} (FT/SEC)	X/D = 5.0 q	T	V_A	V_B	X/D = 8.0 q	T	V_A	V_B	X/D = 12.0 q	T	V_A	V_B
0	.49 / .161	445	321.5	183.8	.35 / .138	325	253	159	.32 / .125	230	227	142	.258 / .111	195	198	130.3
.1	.495 / .164	415	318	183		270			.246 / .132	215	197	144.2	.235 / .100	195	190	123.8
.2	.384 / .119	275	256	142.8	.278 / .124	230	211.5	141.4	.22 / .142	205	185	148.3	.246 / .106	185	192.2	126.2
.3	.172 / .0605	208	163.8	97	.204 / .104	195	175	126	.262 / .125	190	199.4	137.5	.24 / .078	175	191.5	105.5
.4	.143 / .024	135	133.8	54.6	.139 / .06	170	142.8	94	.226 / .084	175	183	111.5	.224 / .084	168	181	111
.5	.168 / .015	125	144	42.9	.134 / .06	150	138	92.5	.166 / .078	160	155	106	.236 / .074	155	184	103
.6	.182 / .05	120	157	82.1	.175 / .06	135	152.7	91.2	.188 / .05	140	162	83.6	.197 / .078	140	166	104.3
.8	.21 / .056	115	168	86	.22 / .074	125	173.2	105	.193 / .068	130	163	96.6	.228 / .056	132	178	88
1.0	.202 / .0605	115	164.8	89.1	.18 / .06	120	156	90	.193 / .068	125	162.3	96.6	.202 / .06	125	166	90.4
1.2	.202 / .0605	115	164.8	89.1	.202 / .072	120	165.3	98.6	.202 / .06	120	165	90	.202 / .06	120	165.2	90
1.4	.198 / .058	115	163	88	.186 / .057	120	158	87.5	.202 / .06	120	165	90	.224 / .05	115	173.2	86.9
1.6	.206 / .0405	115	166.2	73.6	.161 / .063	120	147	92					.236 / .07	115	178	97.5

Y/D	X/D = 16.0 q	T	V_A	V_B	X/D = 17.0 q	T	V_A	V_B	X/D = 18.0 q	T	V_A	V_B	q	T	V_A	V_B
0	.35 / .158	300	249.5	167.3	.318 / .159	265	232	164	.226 / .078	155	181	105.8				
.1	.335 / .138	280	240.5	160.2	.306 / .158	242	223.8	160.9	.262 / .075	155	194	103.7				
.2	.32 / .144	250	230	154.3	.26 / .139	225	204	149	.224 / .072	155	179.4	101.7				
.3	.288 / .124	218	214	140	.213 / .116	205	182	234	.22 / .074	150	177	102.4				
.4	.21 / .11	192	178.2	129.2	.186 / .116	180	167	131.5	.213 / .066	150	174	96.8				
.5	.16 / .082	170	153.3	109.9	.251 / .081	160	199.4	108	.224 / .072	148	178	101				
.6	.176 / .056	155	158.8	89.6	.199 / .073	150	168.3	102	.209 / .087	145	172	111				
.8	.188 / .049	135	161.9	82.5	.168 / .055	132	152.2	87	.202 / .06	140	168.3	91.6				
1.0	.178 / .051	125	156	83.4	.19 / .073	122	160.8	99.5	.175 / .058	135	156	89.6				
1.2	.20 / .073	118	164.1	99.1	.176 / .062	120	154.2	91.6	.168 / .062	130	152.3	92.5				

TABLE IV PULSED FLOW

$\frac{Y}{D}$	$\frac{X}{D}$	$q_{AMP.}$ LB/IN^2	q_{BASE} LB/IN^2	T °F	V_{AMP} FT/SEC	V_{BASE} FT/SEC
0	3.0	.385	.156	360	271	172.8
	4.0	.350	.148	375	261	164.8
	9.0	.28	.145	225	211.5	152.3
	10.0	.251	.134	220	199.3	146
	24.0	.184	.063	140	160.9	94
	36.0	.119	.056	130	124.2	87.7
	48.0	.130	.036	130	133.9	70.4
	72.0	.072	.045	125	99.1	78.4

BIBLIOGRAPHY

1. Burton, C. J., "Preliminary Investigation of the Mixing of a Pulsating Air Jet in a Steady Secondary Air Flow." Master's Thesis, University of Minnesota, 1951.

2. Godsey and Young, Gas Turbines for Aircraft. McGraw-Hill, 1949.

3. Corrsin, S., and Uberoi, M. S., "Further Experiments on the Flow and Heat Transfer in a Heated Turbulent Air Jet." NACA Technical Note #1865, April, 1949.

4. Knottage, H. B., "Turbulence-Fundamental Frontier in Air Flow." Heating, Piping and Air Conditioning, April, 1949.

5. Forstall, Jr., W., and Shapiro, A. H., "Momentum and Mass Transfer in Coaxial Gas Jets." Journal of Applied Mechanics, Vol. 17, No. 4, Dec., 1950.

6. Squire, H. B., and Trouncer, J., "Round Jets in a General Stream." Aeronautical Research Council Technical Report R & M No. 1947, 1944.

7. Ribner, H. S., "Field of Flow About a Jet, and Effect of Jets on Stability of Jet Propelled Airplanes." NACA War Report L-213.

8. Cleeves, V., and Boelter, L. M. K., "Isothermal and Non-isothermal Air Jet Investigations." Chemical Engineering Progress, Vol. 43, 1947.

9. Prandtl, Z., "Bericht uber Untersuchugen Zur ausgebildeten Turbulenz." Z. angew. Math. Mech. 5, 1925.

10. Tollmein, W., "Berechnung Turbulenter Ausbrectungs-vorgagne." Z. angew. Math. Mech. 6, 1926.

11. Kuethe, A. M., "Investigation of the Turbulent Mixing Regions Formed by Jets." Journal of Applied Mechanics, Vol. 57, 1935.

12. Taylor, G. I., "The Transfer of Vorticity and Heat Through a Fluid in Turbulent Motion." Proceedings of the Royal Society of London, Series A, Vol. 135, 1932.

13. Howarth, L., "Concerning the Velocity and Temperature Distributions in Plane and Axially Symmetrical Jets." Proceedings of The Cambridge Philosophical Society, Vol. 34, 1938.

14. Tomotika, S., "Application of the Modified Vorticity Transport Theory to the Turbulent Spreading of a Jet in Air." Proceedings of the Royal Society of London, Series A, Vol. 165.

15. Lin, "Velocity and Temperature Distribution in Turbulent Jets." Unpublished report of California Institute of Technology, 1940.

16. "An Experimental Analysis of the Mixing of a Pulsating Air Jet at Varying Frequencies in a Steady Air Flow." E. A. Robie, Master's Thesis, University of Minnesota, 1952.

APPENDIX

RELATIONS USED

1. MASS FLOW:

FROM ASME POWER TEST CODE, 1949.

$$w = .668\, A_2\, KEY \sqrt{\rho_1 \Delta P}$$

2. REYNOLD'S NUMBER:

$$Re = \frac{\rho V D}{\eta}$$

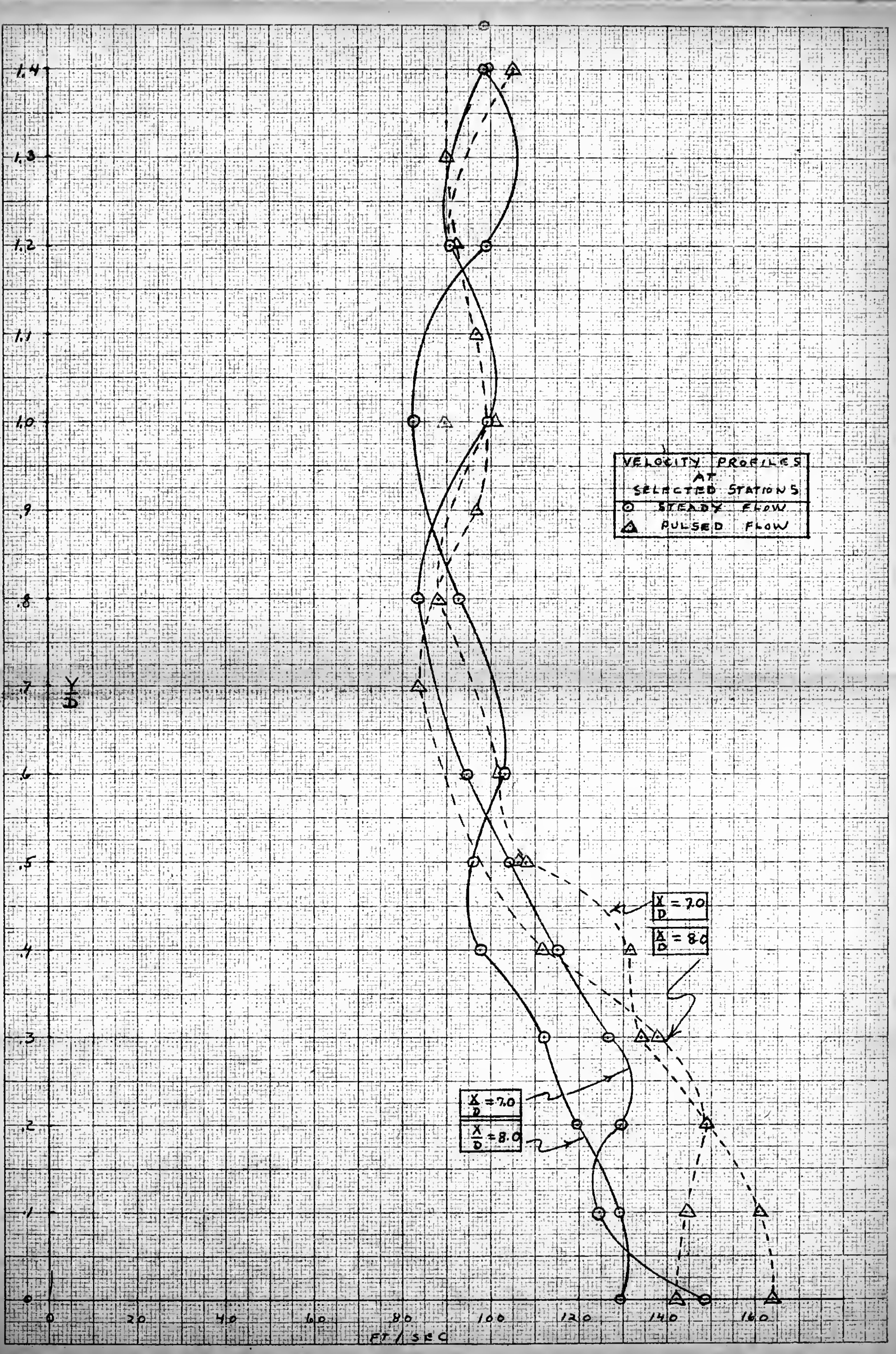
3. MOMENTUM (DENSITY AND VELOCITY VARIABLE):

$$MV = \Sigma\, \rho V^2 A$$

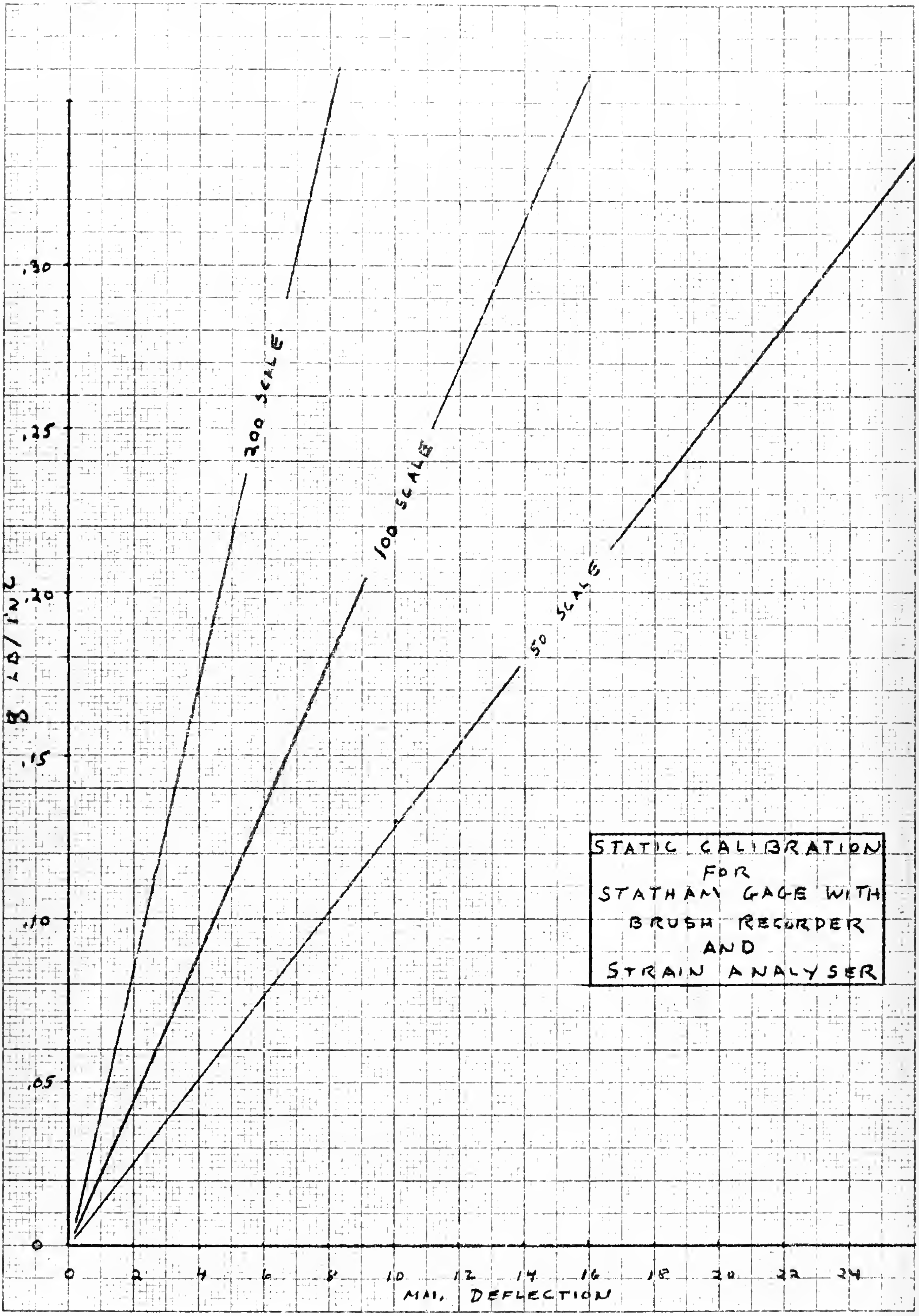
$$\Sigma q = \Sigma\, \tfrac{1}{2} \rho V^2$$

$$\Sigma 2q = \Sigma\, \rho V^2$$

$$MV = 2 \Sigma\, q A$$



VELOCITY PROFILES
AT
SELECTED STATIONS
STEADY FLOW
PULSED FLOW
X/D = 7.0
X/D = 8.0
X/D = 7.0
X/D = 8.0
Y/D
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
0
20
40
60
80
100
120
140
160
FT / SEC



STATIC CALIBRATION FOR STATHAM GAGE WITH BRUSH RECORDER AND STRAIN ANALYSER
200 SCALE
100 SCALE
50 SCALE
LB/IN.2
.30
.25
.20
.15
.10
.05
0
0
2
4
6
8
10
12
14
16
18
20
22
24
MM. DEFLECTION

Thesis 17333
E77 Evans
The mixing of a hot pulsating air jet in a cold secondary air flow.